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CONCEPTS STUDY FOR NANOSECOND RISETIME
MULTI-MEGAJOULE IMPULSE POWER SYSTEMS

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This report considers the concepts, techniques, and limitations of means for controlling the flow of extremely high electric currents and the production of very rapid rates of change of current through a load. Impulse power systems are being incorporated in an increasing number of applications in military and research apparatus. As power and current risetime requirements are increased, more difficulties are encountered by the designer in producing an effective system.
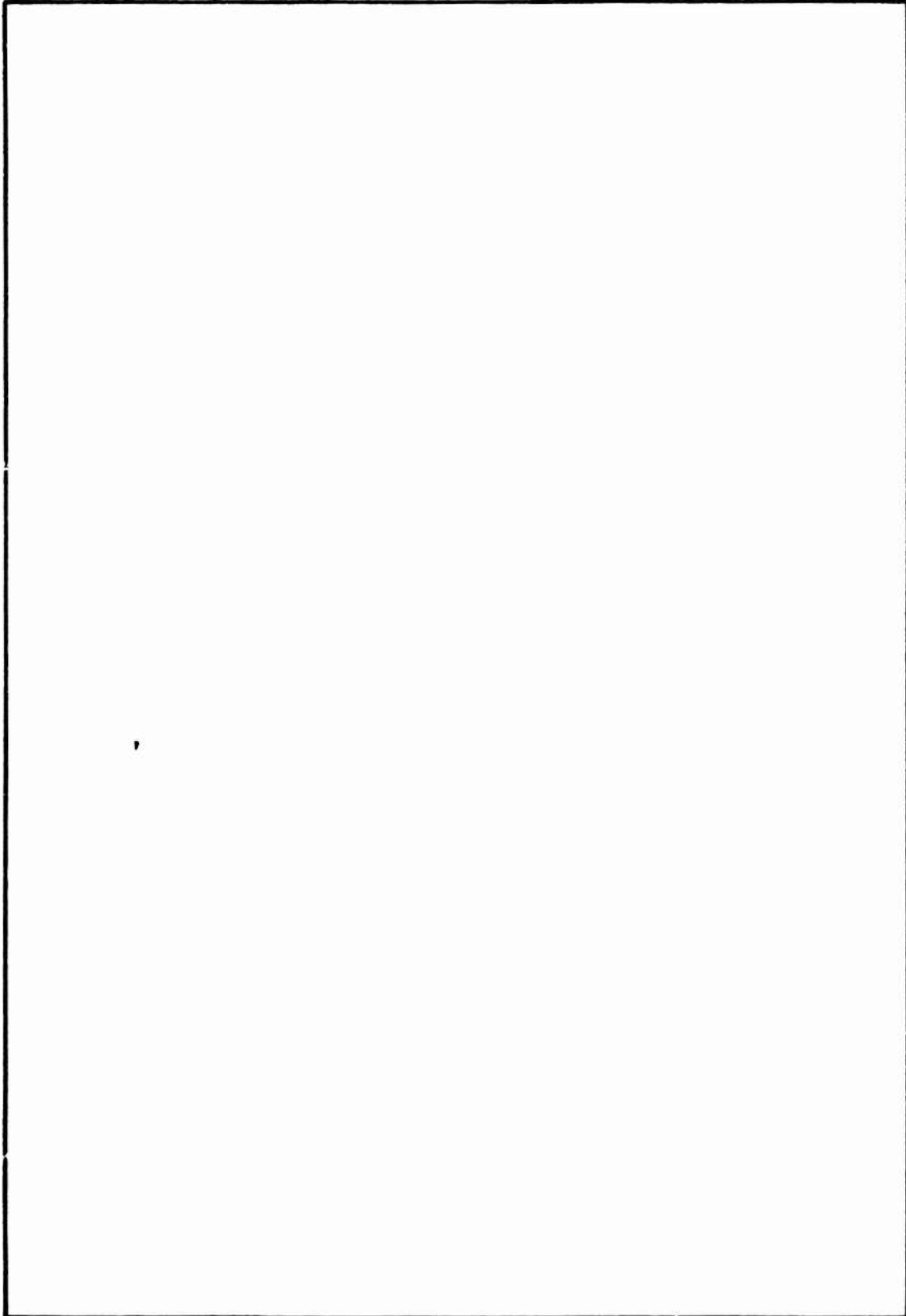
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1. Objective

This report considers the concepts, techniques, and limitations of means for controlling the flow of extremely high electric currents and the production of very rapid rates of change of current through a load. Impulse power systems are being incorporated in an increasing number of applications in military and research apparatus. As power and current risetime requirements are increased, more difficulties are encountered by the designer in producing an effective system.

2. Background

Methods of control of high electrical energies fall into three categories. These categories will be discussed in the following paragraphs.

a. Circuit-Opening Switches

In attempting to halt the flow of a large electric current, one encounters the problem of inductive voltage transient. As one attempts to increase the speed of switching (larger values of di/dt), the transient voltage becomes even larger, ultimately causing switching failure. The cessation of large electric currents with fall times of nanoseconds is beyond the capability of switches with mechanically moving components.

The nonlinear series fuse element has, for many years, been used to stop the flow of electrical current, the most common application being the standard household fuse. This type of fusable link uses normal joule deposition (and the attendant resistivity changes) to heat the fuse material to its melting point. Such opening switches are easily designed and are quite effective as long as the current fall-times required are moderate. For larger values of di/dt, one must use a different technique, i.e., that of the "exploding wire" [1]. Exploding wires (and foils) are distinctly different from normal fuses. The current characteristic of a typical exploding wire is shown in Figure 1. As the electric current pulse is applied at time T_0, the fuse-link rapidly heats through the fusion temperature and through the normal temperature of vaporization until at some time T_1 the internal pressures exceed the forces of magnetic pinch and inertia. At this point ("transplosion"), the superheated vaporized fuse begins expansion and its electrical conductivity greatly decreases so that between times T_2 and T_3 ("pause time") very little current flows. As the vapor becomes less dense, it becomes possible for impact ionization to take place; if this happens, the path becomes very conductive between times T_3 and T_4
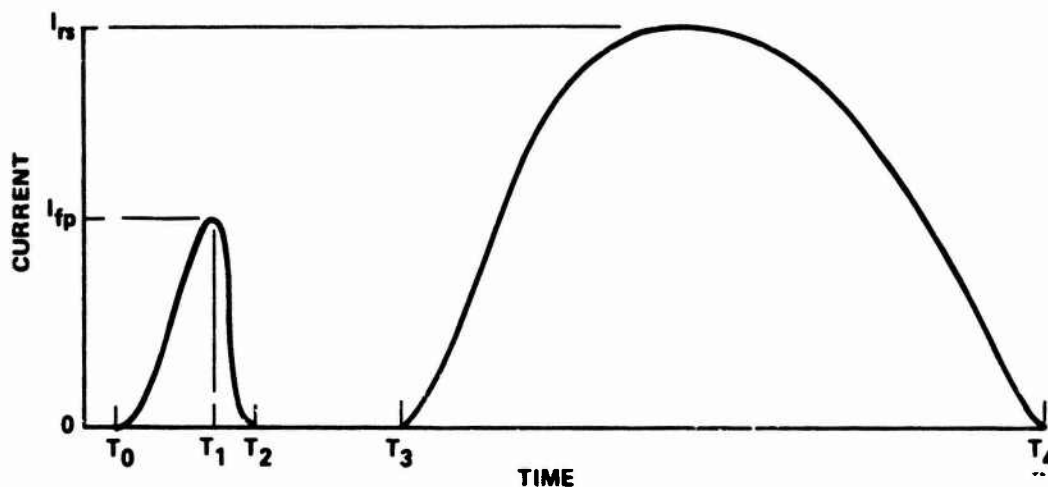
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Figure 1. Current-time characteristic of a
typical exploding wire.

("restrike"). The restrike current pulse must be eliminated or delayed,
by enhancement of the pause time, beyond the period of interest in order
for an exploding conductor to be used as an opening switch.

Several methods may be used to delay or eliminate the onset of the
restrike current. The most direct method is to make the exploding link
long so that the electric field is of such values that ionization of the
expanding metallic vapor becomes unlikely. A practical limit of elec-
tric field for no restrike has been seen to be approximately 61 kV/m
for copper wires in air [2]. For many applications, the simple lengthen-
ing of the exploding link is undesirable. It has been shown that the
energy required to explode a link varies directly as the length of the
link [3], moreover, the link inductance also varies directly as its
length [4]. For circuits required to operate with large values of
di/dt, the switch inductance must be kept to a minimum.

The application of a magnetic field to the exploding link can make
possible higher working electric fields, i.e., shorter length for a
given voltage. Researchers have shown that a magnetic field oriented
axially to an exploding wire will make operation to approximately 68
kV/m possible [2]. A magnetic field applied transversely to the flow
of current in the exploding link will also have a usable effect. In
this instance a force exists governed by:

$$F = I\ell \times B \quad ,$$

where

    F = force in Newtons

    I = current in amps

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ℓ = the length of wire in the magnetic field in meters

B = the magnetic field intensity in Wb/m^2.

Experiments performed with purposely-overstressed exploding copper
wires in air field strengths ranging from 140 to 400 kV/m for axial and
transverse magnetic field orientations [5] have shown the transverse
field to be far more effective than the axial field in producing delay
of restrike. A disadvantage of this method for enhancement of the
performance of an exploding link is the requirement for either massive
permanent magnet structures or power-consuming electromagnets.

The containment of the exploding link by dielectric media has
shown to be at least as beneficial as the use of magnetic fields and
can have several other desirable effects [6][7]. Generally, for
containment-packaging, the exploding link is made into a thin foil and
folded in a zig-zag pattern with dielectric sheets interleaved between
the plates of a low-inductance parallel-plate transmission line. Such
a configurati n produces an extremely low inductance switch because
each folded section tends to cancel the inductance of the last and
the foil, being wide, produces an inductance characteristic inversely
proportional to the width [4]. Experiments have shown that the induct-
ance of a folded foil approaches a value of approximately one-third that
of a foil of equal upstream-downstream dimensions, even though the foil
active length can be many times longer for the folded configuration [8].
Experimental work has shown that a contained folded foil subjected to a
fast rising current pulse can be made to open in approximately 100 nsec
and will withstand 2.5 MV/m field strength without restrike [9]. These
experiments were performed [10] using metallic fuses and have produced
output voltages of approximately 0.5 MV, rising to this value in 20 to
30 nsec. In this case, the fuses took the form of thin foils wrapped
around the end of an extension of the insulation (polyethylene) between
conductors which form an inductive store.

The preceding data and trends show that an exploding link of proper
configuration and design can be an effective circuit-opening switch for
power levels into the terawatt regime. Moreover, such switching can be
made quickly by this means.

b. Circuit-Closing Switches

To cause electric current flow in a circuit one must pro-
vide a completed low-resistance path. This is most often accomplished
by mechanically inserting a metallic connection between the source
terminal and the load terminal (i.e., a switch or relay). If the poten-
tials are above a few hundred volts (as they usually are for high-power
systems) one may use other means to accomplish circuit closure. If the
source and load terminals are closely spaced but separated by some
dielectric media, a nonconducting gap will be formed in the circuit.
As the source voltage rises, the dielectric will be overstressed even-
tually and will break down electrically, permitting a highly-conductive

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electric arc to form between source and load, thereby completing the circuit. Such spark-gap devices are capable of being designed to break down at very precise levels with rapid current risetimes and are repeatable without servicing if a gaseous or liquid dielectric is used.

The dielectric strength of insulators for slow to moderate values of dv/dt has been the subject of study by many. Accurate values of electric strength and general trends are known for many materials [11]. In the design of a spark-gap switch, one has several factors which may be varied to produce the desired performance. The resistive phase of spark-channel development is a major component of the transition time from the nonconductive state to the highly-conductive state of a spark-gap. For gas-insulated spark-gaps, the time duration of the resistive phase is [12]:

$$T_R = \frac{88}{Z^{1/3} F_1^{4/3}} \left(\frac{\rho}{\rho_o}\right)^{1/2} nsec$$

where

Z = impedance of the source (ohms)

F_1 = electric field strength in the gap (10 kV/cm units)

ρ = density of the gas in the gap

ρ_o = density of air at standard conditions.

For the designer of a spark-gap switch this shows what parameters must be controlled and what parameters may be varied to suit conditions. For example, to minimize T_R one can increase Z or F_1 or both. For any particular desired breakdown voltage, one may increase F_1 by using closer gap spacing and higher gas pressures. Although higher pressure will cause a larger value of ρ the net result on T_R is to decrease because F_1 is to the 4 3 power. Alternately, dielectric gases (as SF_6) may be used to permit closer gap spacing. The source impedance may be varied to higher values to aid in fast gap response, but this is not generally done because that factor is to the 1/3 power. If (as usually is the case) the source must deliver sizable electric energy to a load, the selection of source impedance is limited. The switching speed for gas-filled spark gaps at moderate power levels is quite rapid [13], but as high powers are required (necessitating changes of Z) they may become undesirably slow, taking up to several hundred nanoseconds.

Spark gaps are often built using liquid or solid dielectric media. Experiments with oil, water, and polythene [12] have substantiated the relation as

$$T_R = \frac{5}{Z^{1/3} F_2^{4/3}} \text{ nsec} \quad ,$$

where F_2 is the electric field strength in the gap in megavolts/centimeter units. Because only a very small separation of electrodes is required in liquids and solids, these switches are much faster in operation than a gas-insulated switch. Solid dielectric switches are generally the fastest in operation. Various techniques of treatment and assembly of such spark gaps have produced current risetimes of a few nanoseconds of power levels of many thousands of megawatts. One such method is the stabbed polythene switch [14]. By this method, a matrix of sharp metal needles is stabbed to a precise depth into the dielectric producing extreme electric field concentrations at their tips and resultant quick breakdown.

Although any of the preceding spark gaps are often triggered into conduction by a third electrode or by photons or ionizing radiation, the switching time of a spark gap is shortest when it is subjected to an extremely fast dv/dt spike. Such a voltage spike permits extreme values of electric field strength to be developed before streamer closure and the subsequent beginning of formation of a highly conducting path. As has been discussed, this condition is most effective in minimizing gap switching time.

c. Combinations of Opening and Closing Switches

The combination of a circuit-opening switch and a circuit-closing switch has been shown to be an effective means for the control of output from an electrical energy source [6, 7]. Extreme difficulties are encountered in obtaining nanosecond risetimes of current from very high energy capacitive stores due to stray inductance and wave propagation time delays in the current conductors. If, however, the circuit of Figure 2 is used, the di dt at the load may be many times greater than possible with direct use of the capacitor bank.
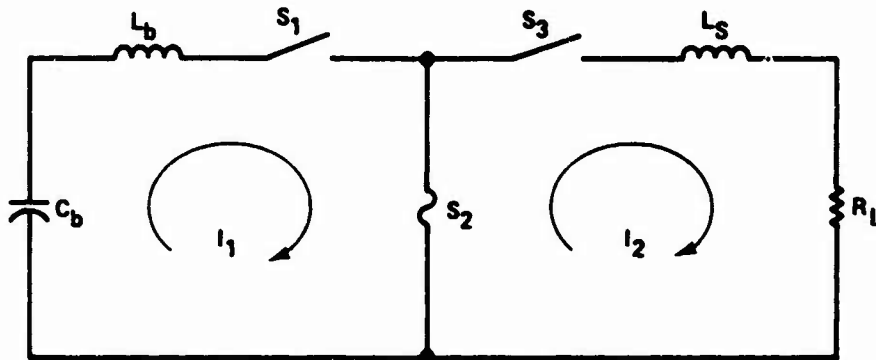

Figure 2. High-speed power system.

In Figure 2, C_b is the capacitance of the storage bank, L_b is the summed inductance of the capacitors and the bank output conductors, and S_1 is the main bank output switch. The circuit comprising of S_2 (a circuit-opening switch) and S_3 (a circuit-closing switch) is inserted between the energy storage bank and the load to be driven (R_L and the stray inductance L_S). One can see that if S_1 is closed, energy from C_b will flow through the exploding-fuse switch S_2 as,

$$I_1 = I_{1_0} \sin \left[\frac{2\pi}{(L_1 C_b)^{1/2}} \right] t$$

the normal discharge of an LC circuit. If S_2 changes to nonconducting at I_1 maximum and S_3 simultaneously closes, the rise of current through the load will be governed by:

$$I_2 = I_1 \epsilon^{-\left(\frac{R_L}{L_S} \right) t}$$

It is seen that the di/dt in the load is governed by the load and its connections rather than by the limits of the energy source. It must be realized from this simple model that S_2 and S_3 were assumed perfect switches and in any close analysis their losses and limitations must be taken into account. However, it has been shown in the previous section that the performance of the opening and closing switches are sufficiently high to be of real use in generating high energy fast risetime current pulses.

3. Conclusions

Note that at this point the high-speed power system of Figure 2 is no longer a simple capacitive source, but is instead a capacitively-charged inductive energy source. Inductive energy stores may take many forms, but all may be used in achieving compact, lightweight, inexpensive, high power deliveries. In the example discussed, the use of the energy stored in the bank stray inductance (L_b) to increase the total

performance has turned what was once a disadvantage into an advantage. If the circuit-opening switch and the circuit-closing switch are developed further along the lines discussed and used with the proper energy source, it will open the way toward impulse-power systems with nanosecond-regime risetimes and energies measured in hundreds of megajoules.

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